Combustion Research Facility News

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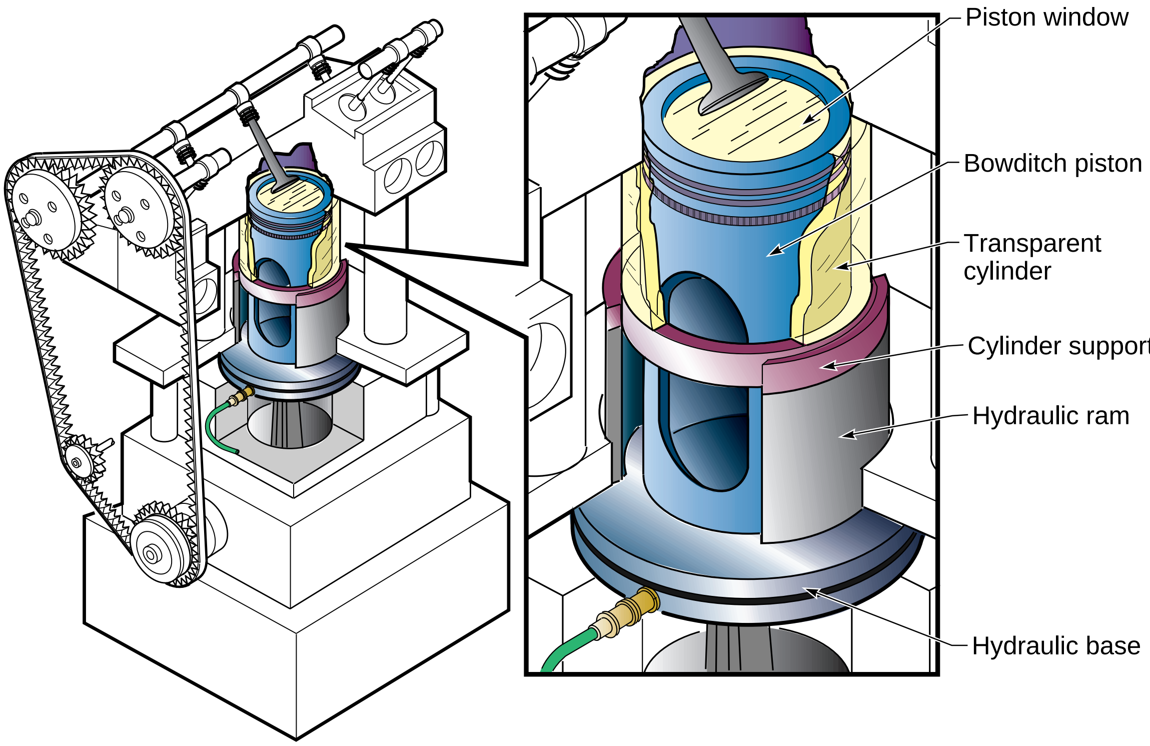
Engines Group Studies In-Cylinder Emissions Formation in Direct-Injection Diesel and Gasoline Engines

The CRF has been closely interacting with U.S. engine manufacturers for more than 20 years to promote fundamental understanding of the in-cylinder processes that govern engine efficiency and emissions. Today, most of the engine research at the CRF is directed toward meeting stringent new emissions standards for passenger vehicles, light-duty trucks, and heavy-duty transport vehicles. Researchers at the CRF employ and develop advanced, laser-based diagnostics in conjunction with experimental hardware that permits optical access while maintaining realistic combustion fluid-dynamic behavior of real engines.

Direct-injection, spark-ignited (DISI) engines offer significant potential for increasing the fuel economy and power density of gasoline engines. The challenge is to take advantage of the higher compression ratios and stratified fuel conditions in DISI engines, while minimizing the formation of exhaust emissions. The CRF's work on DISI engines includes investigations of how fuel spray interacts with the air charge and piston bowl, preparation of appropriate air-fuel vapor mixtures at the spark plug prior to ignition, identification of the extent and effect of liquid fuel deposits on cylinder surfaces, characterization of flame development, and identification of in-cylinder processes that generate soot, unburned hydrocarbon, and NO_x emissions.

In diesel engines, control of the formation of particulates and NO_x has assumed ever greater importance with the advent of more stringent emission standards. The physical processes important in the control of these compounds are complicated in high-speed, direct-injection (HSDI) diesels by the strong swirling fluid motion that exists within the bowl during combustion.

A representative sample of the work performed at the CRF in the engine program is described in the three articles that follow.



This schematic of the transparent quick-release drop-down cylinder shows experimental hardware that allows optical access while achieving realistic engine geometry. The transparent cylinder and piston window provide the viewing ports for laser-based diagnostics.

Spray/Piston-Bowl Interaction Investigated in a Direct Injection Gasoline Engine

Direct-injection, spark-ignited (DISI) gasoline engines offer the potential of significantly better fuel economy (5–15%) than today's port-injected engines. The potential efficiency increase is a result of minimizing engine throttling losses and increasing compression ratios. Fuel economy is maximized when the charge is near stoichiometric near the spark plug, but lean in the surrounding area. The higher compression ratios can be obtained because engine knock is avoided by the charge cooling action of the spray and leaner operation. The challenge is to achieve stratified conditions while preventing fuel from dispersing into concentrations too dilute to maintain combustion, or conversely, concentrating into regions fuel-rich enough to generate particulate matter.

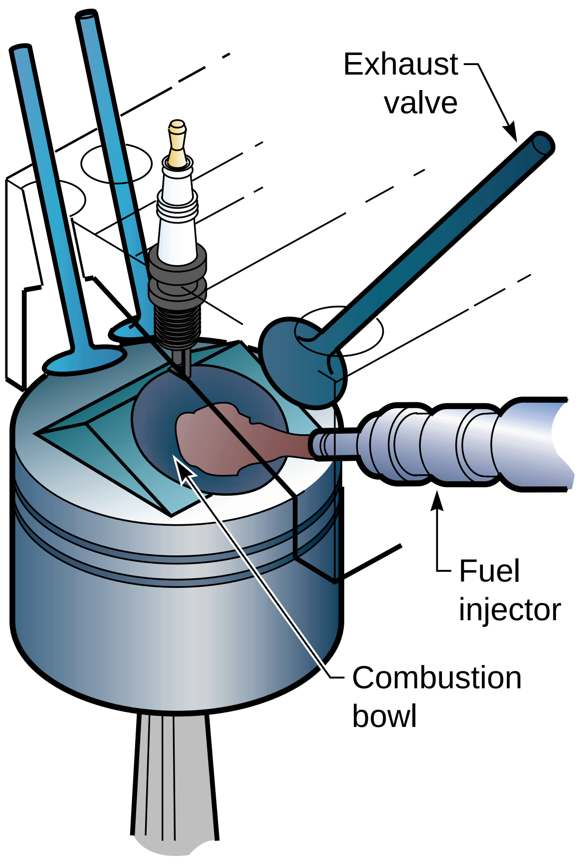


Figure 1. Conceptual cutaway drawing of the piston and cylinder head used for experiments to study the interaction of fuel and a spherical piston bowl in a direct-injection gasoline engine. Fuel is injected via a high-pressure injector mounted at a 40-degree angle from the horizontal. The spray impinges onto the spherical bowl on the piston crown, which redirects the spray towards the spark plug mounted in the center of the chamber. The fourth valve is not shown to simplify the cutaway drawing.

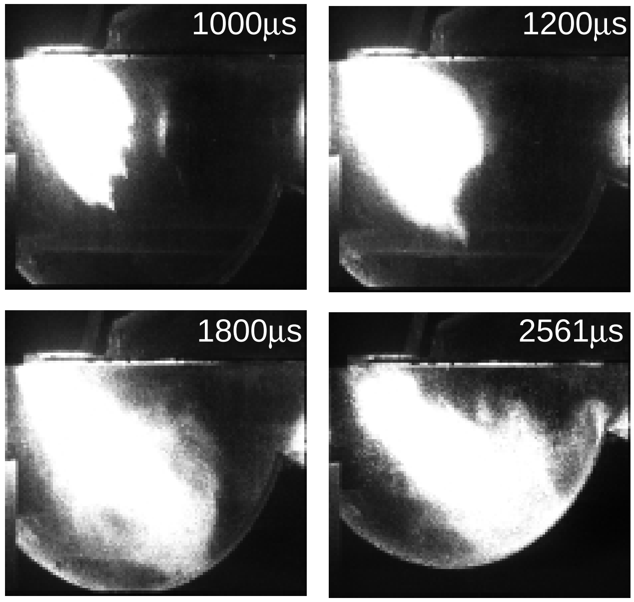
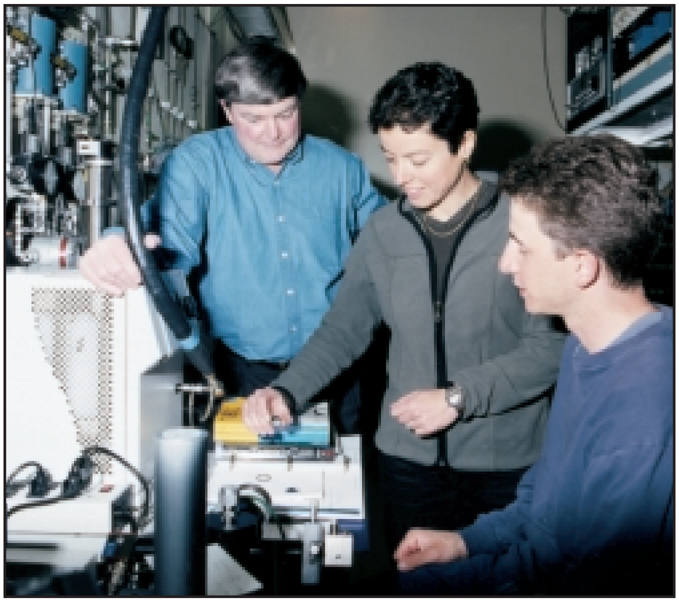


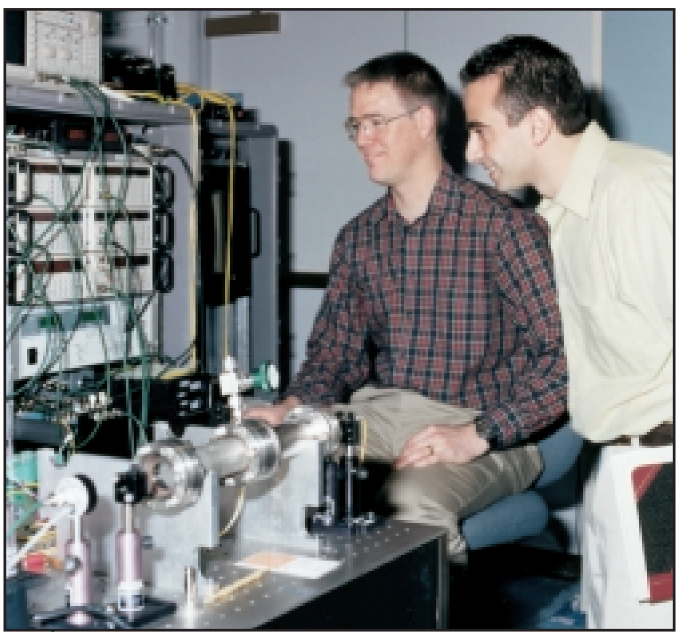
Figure 2. Mie scatter from a sequence of side-injected spray impinging onto a two-dimensional piston bowl. The frames pictured were taken at 1000, 1200, 1800 and 2561 μs from the start of injection. The very bright regions represent a high density of fuel droplets, while the gray areas show more dispersed fuel droplets.

Simone Hochgreb has been investigating the physics of the combustion process in a DISI engine fitted with quartz viewing windows. In this engine, fuel is injected between the intake valves at a 40-degree angle from the horizontal onto a spherical piston bowl (Figure 1). The bowl guides the mixture towards the spark plug as the piston is moving up.

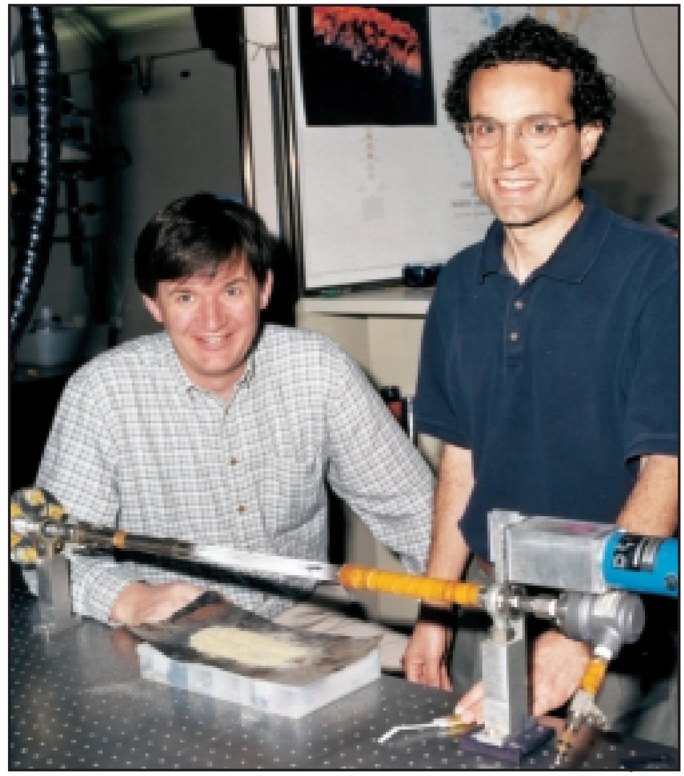
The investigation makes extensive use of visualization capabilities. The behavior of the spray and the charge mixture, including the head pent-roof region, can be seen through quartz windows. A two-dimensional version of the three-dimensional piston, which has a carved cylindrical pattern of the same radius as the three-dimensional bowl, is used to permit line-of-sight visualization of the interaction between the spray and bowl. Figure 2 illustrates the spray-surface interaction in this two-dimensional version of the piston bowl. The investigation is now focusing on how liquid fuel that impinges on the wall becomes a source of hydrocarbon emissions. A three-dimensional quartz piston bowl is now being added to allow visualization of the charge through the bottom of the cylinder.



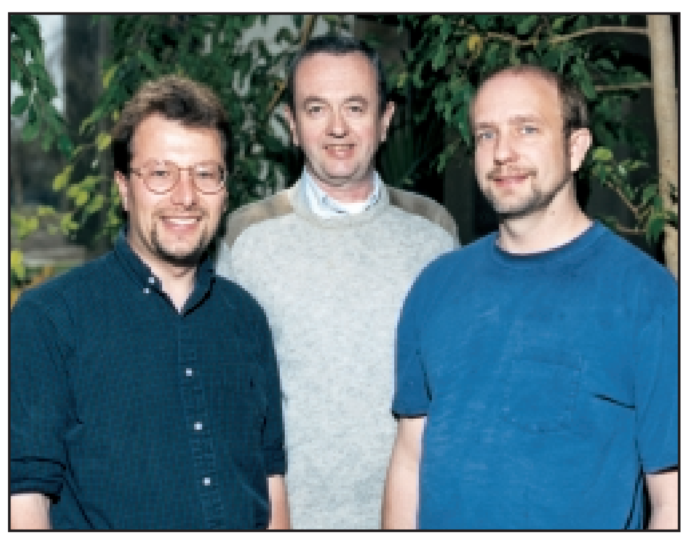
David Kayes (right) has spent the past six months at the CRF working with Simone Hochgreb and Pete Witze on laser-induced incandescence (LII) studies of particulate matter. David refined an LII model developed at Sandia and set up a scanning mobility particle sizing capability with a mini-dilution tunnel for direct calibration of LII on diesel exhaust.



Jimmy Daghlian (right), a graduate student from the University of Utah, is working with Chris Shaddix on the design and implementation of diagnostics for transient soot concentration and temperature measurements in fire environments. Attenuation of electronically modulated diode lasers and two-color emission pyrometry are being measured in an unsteady, buoyant diffusion flame of acetylene at the CRF and in large-scale pool fires of JP-8 aviation fuel at the Lurance Canyon Burn Site located at Sandia/NM. Similar work is being initiated by Jimmy at the University of Utah as part of the ASCI-Alliance C-SAFE project.



Marc Rumminger (right) recently completed a postdoctoral appointment at Sandia National Laboratories working with Larry Baxter in the Multifuel Combustor Laboratory. During his appointment, Marc investigated the effects of fuel impurities in biomass, coal, and black liquor combustion on the formation of deposits like those shown on the reactor probe in the photograph. Marc has accepted a job at Ceryx, Inc. in Southern California.



Ken Aniolek (left) is leaving the CRF to take a position with Corning, Inc. He has been working with Bob Gallagher (center) and Tom Kulp on the development of technologies for use in the remote sensing of gaseous species

Awards

Bastress and Adams Awards Presented

On April 12, 2000, the E. K. Bastress Award was presented to Steel Sensors Team members Sarah Allendorf, Gary Hubbard, David Ottesen, Jimmy Ross, and Allen Salmi and the O. W. Adams Award to Richard Behrens. The Bastress Award is dedicated to the memory of Dr. E. Karl Bastress, who envisioned, implemented, and guided the first energy-conservation-related combustion research activities for the DOE. The Award honors a Sandia employee or team of employees who have significantly contributed to the strong and effective coupling of combustion research programs to the needs of United States industries. The Steel Sensors Team was cited for their work in developing high-quality sensors for the United States steel industry. Dave Ottesen, who spoke for the group, recounted his excitement in seeing the first clear hot-band CO spectrum emerge from blast furnace exhaust gases at the Bethlehem Steel Company in Baltimore.

The Adams Award recognizes exemplary contributions that blend excellence in science with other accomplishments that help make the CRF the paradigm for government-sponsored User Facilities. This year's winner, Richard Behrens, was recognized for sustained contributions to the understanding of the thermal decomposition of energetic materials. The Adams Award is given in the name of Bill Adams, the CRF's original, and very supportive, DOE sponsor. In accepting the Adams award, Rich Behrens looked back fondly on his 30-year career at several DOE labs.

Adams Award winner Rich Behrens (second from right) and Bastress-Award-winning Steel Sensors Team of (left to right) Gary Hubbard, Sarah Allendorf, Dave Ottesen, Allen Salmi, and Jimmy Ross.

BES Peer Review

On March 20-22, 2000, external peers reviewed CRF's DOE/BES-supported combustion sciences research program. Members of the review panel were (front row left to right) Stan Staten (DOE), Carolyn Kaplan (Naval Research Laboratory), and Bill Kirchhoff (DOE) and (back row left to right) Allan Laufer (DOE), Walter Lempert (Ohio State University), Phillip Varghese (University of Texas), Patrick Vaccaro (Yale University), and Thomas O'Brien (NETL).

Events

Particulate Diagnostics Workshop Scheduled for July 20-21

Sandia National Laboratories and the U.S. Department of Energy are sponsoring a workshop on July 20-21, 2000, which is intended to further the development of diagnostic tools and techniques needed to study nano-scale particulates formed in reciprocating engines. The workshop will bring together experts from industry, academia, and research institutions to review current research, future diagnostic needs, and ways to leverage resources. Those interested in attending should contact April Cunningham at the CRF (acunni@sandia.gov).

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Director: William J. McLean
Mail Stop 9054

Editor: Howard Lentzner
Email: hllentz@sandia.gov
Designer: David French

Late-Cycle Soot Measurements in a High-Speed, Direct-Ignition Diesel Engine Support Computational Results

Researchers at the CRF, in collaboration with partners at the University of Wisconsin and Wayne State University, are investigating the in-cylinder mixing and combustion processes that occur in high-speed, direct-injection (HSDI) diesel engines. HSDI engines differ from quiescent-chamber, heavy-duty engines in that the highly swirling flow, as well as spray/wall and flame/wall interaction effects, can significantly influence the combustion process. This research program directly supports the Partnership for a New Generation of Vehicles (PNGV), an agreement between the U.S. government and the big three U.S. automotive manufacturers to develop vehicles with up to 80 mpg fuel economy by the year 2004. Meeting the proposed 2004 standards for emissions of particulate matter and NO_x will be a major challenge, and will require both lower engine-out emission levels and more effective exhaust gas aftertreatment. Research at the CRF is directed at obtaining a better understanding of the processes that influence emission formation in the cylinder, such that engine optimization and design for minimal engine-out emissions can proceed on a sound scientific basis.

The research program consists of three components: optical imaging studies performed by Paul Miles at Sandia; conventional performance and emissions measurements performed by Naeim Henein and Ming-Chia Lai at Wayne State University; and multi-dimensional modeling performed by Rolf Reitz and Keith Richards at the University of Wisconsin. The engine facility at Sandia achieves optical access through an extended piston arrangement and a quartz piston top, as well as through access windows in the cylinder walls and in the head. This extended optical access has been achieved with minimal modifications to the engine geometry, such that the combustion process in the optical engine is as close as possible to the combustion in the unmodified engine at Wayne State.

Late-cycle oxidation of particulate matter provides an example of how the three program components interact to further our understanding of the combustion process. Figure 1a shows the spatial distribution of hot, radiant particulate matter measured in the optical engine, which serves to mark the spatial locations of the late-cycle oxidation. In Figure 1b the contours of the in-cylinder heat release, as computed from the multidimensional model, are shown. The close correspondence between the locations of the experimental and computed oxidation zones lends support to the computed results, which to date have been subjected to little or no experimental verification. By examining how the locations and rates of late-cycle oxidation vary as the engine operating parameters are varied, and how the observed in-cylinder changes influence the conventional emissions measurements, significant advances in our understanding of the important processes influencing particulate oxidation and emissions can be achieved.

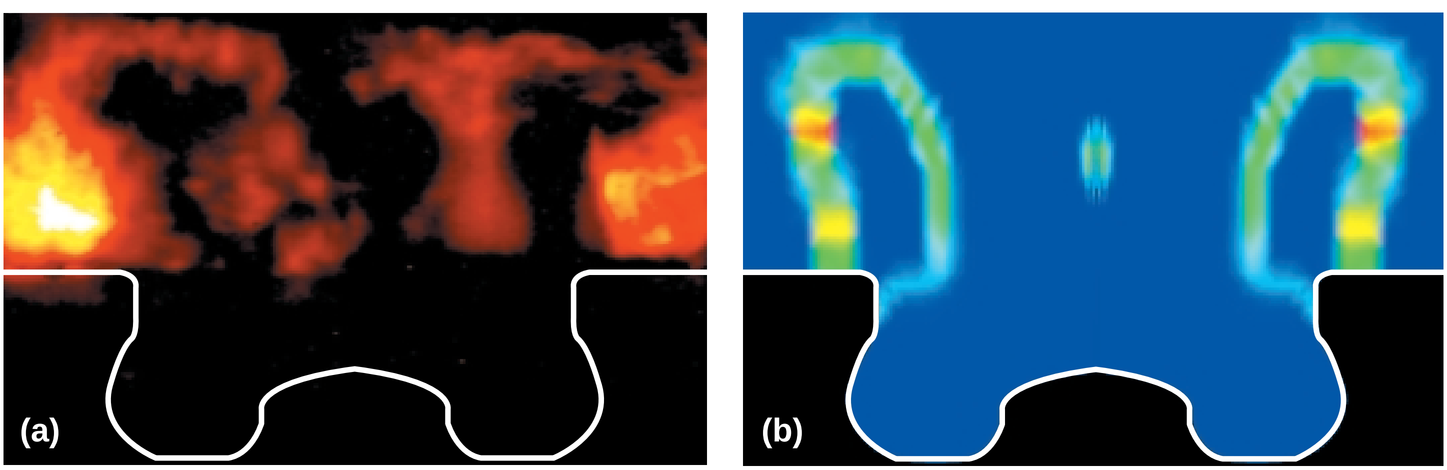

Figure 1. Comparison of late-cycle oxidation of particulate matter as measured as luminous soot in the optical engine (a) and as a plot of heat release computed from a multidimensional model at the University of Wisconsin (b). The white lines trace the relative position of the piston-bowl lip.

Optical Diagnostics Developed for Real-Time Measurement of Nano-Size Particulate Matter

In response to stringent emissions standards, the total mass of particulate matter in diesel exhaust has been reduced dramatically over the last two decades. However, concern has been expressed recently that although the mass of discharged particulates is lower, the total number of particles emitted has actually increased by several orders of magnitude. Although more numerous, these particles cannot be seen because their average particle size has decreased dramatically; most of these particles are less than 0.5 µm in size. Additionally, there is growing evidence that gasoline engines (particularly those that employ direct injection) also emit nano-size particles in quantities that could be of concern. Epidemiological studies suggest that particulate matter in the nano-size range may be particularly deleterious to human health.

The current standard for measuring particulate matter is a gravimetric procedure in which samples are collected on filter paper and weighed. Because it takes a long time to collect a measurable mass of nano-size particles, the technique cannot be used to measure particulate emissions during transient engine operation, the conditions under which most of the particulate matter is emitted. In response to this need for a better technique, a team consisting of Pete Witze, Bob Green, Simone Hochgreb, Hope Michelsen, Chris Shaddix, and visitor David Kayes have initiated a program to develop optical techniques for the real-time measurement of particulate matter in exhaust flows. Our initial effort is limited to the simultaneous application of laser-induced incandescence (LII) and elastic scattering, but future plans include multiangle detection for the extraction of statistical information describing ensembles of particle aggregates. David and Simone are also developing a computer model to help guide data analysis.

In our prototype optical cell, the exhaust flow is vertical, and diametrically opposed photodetectors measure the signals generated by a Nd:YAG laser beam. A mini-dilution tunnel conditions the exhaust from a four-cylinder, turbocharged production diesel engine, and the cell is calibrated with a scanning mobility particle sizer. A digital oscilloscope is used to acquire data through a PC interface. Figure 1 shows LII measurements obtained during engine startup, which demonstrate the real-time capabilities of the technique. We have also been able to show that the LII is sensitive to exhaust gas recirculation and load transients.

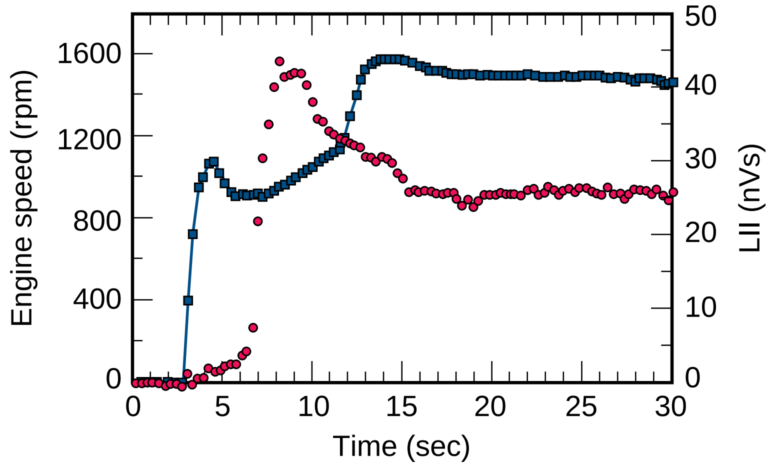

Figure 1. Laser-induced incandescence (LII) measurements obtained in real time from a TDI diesel engine during start-up. The LII signal (red data points) is proportional to the soot volume fraction, and is offset from the engine speed (black data points) because of the time it takes for the exhaust to reach the optical cell.

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Sandia National Laboratories
Mail Stop 9056
P.O. Box 969
Livermore, California 94551-0969

http://www.ca.sandia.gov/CRF/

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